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Games of Climate Change with International Trade

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Abstract. We analyse games of greenhouse gas emission reduction in which the emissions and the emission reduction costs of one country depend on other countries' emission abatement. In an analytically tractable model, we show that international trade effects on costs and emissions can either increase or decrease incentives to reduce emissions and to cooperate on emission abatement; in some specifications, optimal emission reduction is unaffected by trade. We therefore specify the model further, calibrating it to larger models that estimate the costs of emission reduction, trade effects, and impacts of climate change. If trade effects are driven by total emission reduction costs of other countries cooperation is slightly more difficult than in the case without trade effects. If trade effects are determined by relative emission reduction efforts in other countries, cooperation becomes easier. Carbon leakage does not affect our qualitative insights, although it does change the numbers.

Key words: carbon leakage, climate change, coalition formation, greenhouse gas emission reduction, international trade, optimal emission control

JEL classification: C72, F00, Q25, Q28

1. Introduction

Climate change is a complex problem with many interactions between countries. The main interactions take place, of course, via the atmosphere. However, national emission reduction policies also influence each other via international trade and investment. Other interactions include those between climate policy and technology, development, nature conservation, environmental protection, and transport. Climate change research only slowly comes to grips with this complexity. This paper explores the interactions between emission reduction strategies and trade effects.

Most game theoretic analyses of international climate policy allow for one interaction only: the climate. In those analyses, greenhouse gas emission reduction is a private good while the atmosphere is a public good. However, this is a distorted representation of reality. Greenhouse gas emission reduction in one country affects other countries in more ways than just via climatic change, particularly via international trade and investment, carbon leakage, and technological development and diffusion. This paper investigates international climate policy with multiple interactions.

Obviously, other authors have realised this as well. The impacts of international trade on the distribution of the costs of climate change are analysed by, amongst others, Bernstein et al. (1999a–c) and Kemfert (2000). The literature on international cooperation and trade is thin, however; see Ioannidis et al. (2000) for a recent review of the international environmental agreement literature. Copeland and Taylor (2000) look at the demand for unilateral emission reduction in a CGE model with international trade in goods as well as emission permits. Le Breton and Soubayran (1997) investigate second-best environmental policies in the presence of international trade. Feenstra (1999) looks at international trade and environmental dumping. Barrett (1997) looks at trade sanctions as a deterrent to free-riding. Alpay (2000) shows under which conditions trade can stimulate environmental protection with the help of general equilibrium model with a game theoretic component. We focus on the question how international trade (a) changes optimal emission reduction and (b) incentives to cooperate on emission reduction. As far as we know, we are the first to do so.

Whether an agreement can be reached depends on the opportunities to reduce conflicts of interests; a bargaining situation contains opportunities to collaborate for mutual benefits (Barrett 1994). As real negotiation processes demonstrate, an agreement between all players is unlikely. It is more realistic that some players act unilaterally in order to maximise their own welfare, while other players form small coalitions. The conclusion that stable coalitions are small has been established for single-issue international environmental negotiations (Barrett 1994; Botteon and Carraro 1997a, b, 1998; Carraro and Siniscalco 1992, 1993; Hoel 1994). Carraro and Siniscalco (1997), Katsoulacos (1996) and Tol et al. (2000, 2001) investigate whether linking international greenhouse gas emission reduction policy and technology policy would enlarge incentives for cooperation. This paper does not link issues, but analyses the case with dual interactions between players, only one of which (greenhouse gas emissions) is actively managed. Here, the second interaction is trade. In Tol et al. (2000, 2001), the second interaction is technology. Barrett (1994) confines himself to *trade sanctions* as a deterrent to free riding. Botteon and Carraro (1997a, b, 1998) confine themselves to carbon leakage.

This paper looks at the effects of international trade and investment and carbon leakage on incentives to abate greenhouse gas emissions and incentives to cooperate on emission reduction. Because of international trade effects, the cost of one country's emission reduction depends on other countries' abatement efforts and costs. Because of carbon leakage, one country's emissions depend on other countries' abatement effort. Section 2 takes an analytical viewpoint. We demonstrate that most relationships of interest are ambiguous – particularly, the effects of international trade and investment on costs and emissions can both increase and decrease a country's incentives to abate emissions and to cooperate with other countries in doing so. Therefore, we introduce a numerical model in Section 3. This is an intertemporal computable general equilibrium (CGE) model of the world economy, designed to answer empirical questions about greenhouse gas emission reduction, international trade and carbon leakage. A simplified version of the model of Section 2 is calibrated to the outcomes of the CGE model. The simple model is used in Section 4. It is analytically tractable and, fully parameterised, used to shed light on the ambiguities of Section 2. Section 5 concludes.

2. Analytical Structure

For convenience, we consider only two countries, labelled as $\{i, j\}$, with $i \neq j$. The case with more countries will be introduced below. Let C_i denote the absolute costs of greenhouse gas emission reduction in country i. Suppose

$$\frac{C_i}{Y_i} = \frac{C_i(R_i, R_j, C_j)}{Y_i} = f_i(R_i) + g_i(R_i - R_j) + h_i(C_j) \tag{1}$$

where R denotes emission reduction (as a fraction of uncontrolled emissions without leakage), and Y is GDP. The cost function consists of three components: the costs of domestic emission reduction $f(.)$, costs associated with the difference between domestic and foreign emission reduction $g(.)$, and costs associated with foreign emission reduction costs $h(.)$. The $g(.)$ function combines the terms-of-trade effect and the dynamic effects of the international capital market. These effects are driven by the domestic prices of energy and energy-intensive goods, which differ in different countries because of differences in regulation. The $h(.)$ functions measures all other effects, particularly a slowing of economic growth in the other country.[1] To put it differently, $g(.)$ captures the relative effects, and $h(.)$ the size effects of international emission reduction policy; together, $g(.)$ and $h(.)$ capture the spillover effects; $f(.)$ captures the domestic effects. Additivity is assumed for convenience.

Let

$$f_i(0) = 0,\ f_i(x) > 0 \text{ if } x > 0,\ \frac{\partial f_i}{\partial x} > 0,\ \frac{\partial^2 f_i}{\partial x^2} > 0. \tag{2}$$

That is, the costs of domestic emission reduction are positive, increasing and convex. The baseline ($R = 0$) is optimal. These are standard assumptions for the costs of greenhouse gas emission reduction.

Let

$$g_i(0) = 0,\ g_i(x) > 0 \text{ if } x > 0,\ \ g_i(x) < 0 \text{ if } x < 0,\ \frac{\partial g_i}{\partial x} > 0. \tag{3}$$

That is, if country i and j abate the same amount, there are no additional costs or benefits to country i; note that this is only strictly true if the two countries are identical; in the analysis below, however, only the slope of g matters. If country j abates less than does country i, country i suffers additional costs. The additional costs or benefits grow with the difference in abatement effort. In a simple trade model, g and x may actually differ in sign; that is, assumption (3) is not met. More expensive energy in one country would simply change its terms-of-trade, for better or worse. In a more realistic model, where specialisations do not change overnight, taxing energy while other countries do not, would entail a loss. The empirical estimates in Section 4 confirm this suspicion. However, for completeness, we also analyse the case in which g and x differ in sign.

Let

$$h_i(0) = 0, h_i(x) > 0 \text{ if } x > 0, \frac{\partial h_i}{\partial x} > 0. \tag{4}$$

That is, if country j faces positive emission reduction costs, some of those costs trickle down to country i, for example, through reduced exports from i to j. The larger the costs to country j, the larger the effect on country i. This size effect has particularly been documented for developing countries, which, despite a fall in world oil prices and an improvement of their terms-of-trade, are generally found to loose from greenhouse gas emission abatement in the OECD.

Although the model (1)–(4) is fairly simple, it covers the relevant effects. Let us reiterate the basic properties. Emission reduction is costly. If a country has a more stringent emission reduction policy than others, that country faces additional costs because of worsening terms-of-trade. *Vice versa*, if a country's policy is less stringent, its terms-of-trade improve. If a country reduces emissions, it grows slower and imports less, inflicting losses on other countries. Babiker et al. (2000), Bernstein et al. (1999a–c), Kennedy et al. (1996, 1997), Piggott et al. (1992), Tulpule et al. (1999) and Whalley and Wigle (1991) discuss the relative size of these effects for different economies and different emission reduction policies.

The model (1)–(4) displays a wide range of behaviour. The costs of emission reduction depend on the emission reduction in other countries. This effect can be positive or negative, depending on the relative sizes of the above mechanisms and the relative sizes of emission reduction. Even in the absence of domestic action, a country can be affected (positively or negatively) by other countries' emission reduction (e.g., Babiker et al. 2000; Tulpule et al. 1999).

The model is completed with carbon emissions and carbon leakage Let

$$E_i^R = (1 - R_i)E_i + k_i(R_j - R_i)E_i. \tag{5}$$

That is, actual emissions E_i^R depend on the emissions without climate policy E_i and emission reductions in both countries.[2] Note that R now denotes emission reductions *in the absence of leakage*, or perhaps "intended emission reduction". With leakage, actual emission reduction may be different. Let

$$k_i(0) = 0,\ k_i(x) > 0 \text{ if } x > 0,\ k_i(x) < 0 \text{ if } x < 0, \frac{\partial k_i}{\partial x} > 0. \tag{6}$$

Thus, emissions increase in country i if country j abates more than does country i. That is, there is leakage from j to i. *Vice versa*, if country i abates more than does country j, its emissions leak from i to j. Leakage only replaces emissions,[3] so that

$$k_1(R_2 - R_1)E_1 + k_2(R_1 - R_2)E_2 = 0. \tag{7}$$

The benefits of avoided climate change B_i are given by

$$B_i = l_i(E_i + E_j) - l_i(E_i^R + E_j^R). \tag{8}$$

We only assume that B is strictly increasing in total emissions; there are no further restrictions on function $l_i(.)$. The optimisation problem is then to minimise the net costs, that is $C_i - B_i$, where the level of emission reduction R_i is the only control variable.

There are a number of possibilities to – logically – extend this framework to n players. This paper mainly uses the following extension:

$$\begin{aligned} C_i &= f_i(R_i) + g_i(R_1, R_2, \ldots, R_i, \ldots, R_n) + \\ &\quad h_i(C_1, C_2, \ldots, C_{i-1}, C_{i+1}, \ldots, C_n) \end{aligned} \tag{1$'$}$$

$$E_i^R = [1 - R_i + k_i(R_1, R_2, \ldots, R_i, \ldots, R_n)]E_i. \tag{5$'$}$$

Equation (8) would be replaced by

$$B_i = l_i\left(\sum_{s=1}^{n} E_s\right) - l_i\left(\sum_{s=1}^{n} E_s^R\right). \tag{8$'$}$$

The model can be solved by considering the first order condition (FOC), which can be represented by matrices; we need to use matrix inversion or Cramer's ruler to get an explicit expression. We do this for the three dimensional case in Section 4.

The effect of spillover and leakage effects on optimal emission reduction is ambiguous, as can be seen from the FOC for the case with two players. For player 1,

$$\begin{aligned} &\left(\frac{\partial f_1}{\partial R_1} + \frac{\partial g_1}{\partial R_1} - \frac{\partial h_1}{\partial C_2}\frac{\partial g_2}{\partial R_1}\right) \Big/ \left(1 - \frac{\partial h_1}{\partial C_2}\frac{\partial h_2}{\partial C_1}\right) = \\ &E_1\frac{\partial l_1}{\partial R_1} + \frac{\partial l_1}{\partial R_1}\left(E_1\frac{\partial k_1}{\partial R_1} - E_2\frac{\partial k_2}{\partial R_1}\right) \end{aligned} \tag{9}$$

and similar for player 2; in (9), the marginal costs are at the left hand side and the marginal benefits at the right hand side. Recall that leakage is just replacement, that is, the emissions of player 1 (2) go up by the same amount as the emissions of player 2 (1) go down. Then the benefits and the marginal benefits are unaffected, that is, the rightmost term of (9) cancels.

Assume, for the moment, that the emission reduction and emission reduction costs of the other country are fixed. Let us first consider the terms-of-trade effect only, that is, $h = 0$:

$$\frac{\partial f_1}{\partial R_1} + \frac{\partial g_1}{\partial R_1} = E_1 \frac{\partial l_1}{\partial R_1}. \tag{9$'$}$$

Even though this terms-of-trade effect can be either positive or negative, the costs at the margin are always positive, that is, $\partial g_1/\partial R_1 > 0$, so that optimal emission reduction is lower with terms-of-trade effects than without. Note that if leakage does not cancel in aggregate – that is, Equation (7) does not hold – then the optimal emission reduction can be both lower and higher. Obviously, in the (unlikely) case that $\partial g_1/\partial R_1 < 0$, this conclusion is reversed – but still unambiguous, unless leakage does not cancel.

Now consider the case with size effects but without terms-of-trade effects, that is, $g = 0$:

$$\left(\frac{\partial f_1}{\partial R_1}\right) \Bigg/ \left(1 - \frac{\partial h_1}{\partial C_2}\frac{\partial h_2}{\partial C_1}\right) = E_1 \frac{\partial l_1}{\partial R_1}. \tag{9$''$}$$

In this case, the marginal costs are the same with and without the size effects and optimal emission reduction is unaltered, as the partial derivatives with respect to C_i are not sensitive to changes in R_i. Leakage, if it does not cancel, could drive optimal emission reduction up or down.

Finally, consider the case with both size and terms-of-trade effects. The terms-of-trade effects still work towards lowering of optimal emission reduction. The size effects are no longer neutral. The third term of the left-hand-side of (9) has an effect opposite to the effect of the second term. The combined effect is ambiguous. If we assume that the countries are similar – $g_1 = g_2$ – what matters is whether $\partial h_1/\partial C_2$ is greater or smaller than unity:

$$\left(\frac{\partial f_1}{\partial R_1} + \frac{\partial g_1}{\partial R_1}\left[1 - \frac{\partial h_1}{\partial C_2}\right]\right) \Bigg/ \left(1 - \frac{\partial h_1}{\partial C_2}\frac{\partial h_2}{\partial C_1}\right) = E_1 \frac{\partial l_1}{\partial R_1}. \tag{9$'''$}$$

If it is smaller, size and terms-of-trade effects work towards lower emission reduction, albeit it is to a lesser extent than without the size effects. If it is greater, size and terms-of-trade effects lead to a greater optimal emission reduction. The strength of the marginal size effect depends, obviously, on emission reduction. Therefore, for small emission reduction, size effects lower emission reduction even further; for large emission reduction, size effects have the opposite effect. Leakage, if it does not cancel, only makes the matter more indeterminate.

Now, if we consider that emission reductions and emission reduction costs are set simultaneously for both countries, the ambiguities of (9) only increase.

So, based on a formal model alone, one cannot say whether spillover effects lead to higher or lower emission reduction, higher or lower emission reduction costs,

Table I. Regions in WAGEM

Abbreviation	Countries
ASIA	India, South Korea, Indonesia, Malaysia, Philippines, Singapore, Thailand, Hong Kong, Taiwan
CHN	China
CNA	Canada, New Zealand and Australia
EU15	European Union
JPN	Japan
LSA	Latin America
MIDE	Middle East and North Africa
REC	Russia, Eastern and Central European Countries
ROW	Rest of the World
SSA	Sub Saharan Africa
USA	United States of America

and thus whether trade effects help or hinder cooperation. The answer depends on the relative strength of the various effects. In the next section, we estimate the effects using a state-of-the-art model for analysing carbon dioxide emission reduction costs, international trade and international investment.

3. CGE

The pay-offs of international emission reduction policies are estimated using an intertemporal general equilibrium model WAGEM (Kemfert 2000). General equilibrium models are especially appropriate to assess economic impacts of alternative climate policy games, see Manne and Richels (1998), Nordhaus and Yang (1998), Bernstein et al. (1999a–c) or McKibbin and Wilcoxen (1999). WAGEM is an intertemporal computable general equilibrium and multi regional trade model for the global economy. The model considers 11 world regions (Table I) that are linked through bilateral sectoral trade flows based on GTAP data of 1995. For each region, a representative agent maximises lifetime utility from consumption. This determines the level of savings. Firms choose investment in order to make the most of the present value of their companies.

In each region, production of the non-energy macro good is captured by an aggregate production function. The production function characterises technology through transformation possibilities on the output side and substitution possibilities on the input side. In each region, a representative household chooses to allocate lifetime income across consumption in different time periods in order to maximise lifetime utility. In each period, households face the choice between current consumption and future consumption, which can be purchased via savings.

The trade-off between current consumption and savings is given by a constant intertemporal elasticity of substitution. Producers invest as long as the marginal return on investment equals the marginal cost of capital formation. The rates of return are determined by a uniform and endogenous world interest rate such that the marginal productivity of a unit of investment and a unit of consumption is equalised within and across countries. Domestic and imported varieties for the non-energy good for all buyers in the domestic market are treated as imperfect substitutes by a CBS Armington aggregation function, constrained to constant elasticities of substitution. Emission limits can be reached by domestic action or by trading emission permits within Annex B countries allocated initially due to regional commitment targets. Those countries meeting the Kyoto emissions reduction target stabilise their mitigated emissions at 2010 level.

Fourteen scenarios are run with WAGEM to get an idea of the costs of carbon dioxide emission reduction. We consider only emission reduction by the European Union (EU15), Japan (JPN) and the USA. In one scenario, all three countries reduce emissions by 10% in comparison to the base year emissions (1990). In three scenarios, two countries reduce their emissions by 10% while the other countries do not reduce at all. In three further scenarios, one country reduces its emissions by 10% while the other countries do not abate emissions. This is repeated for a 20% emission reduction. This makes 14 scenarios:

All: All Annex B countries reduce emissions by 20% (10%)
EUuni: EU15 reduces emissions unilaterally by 20% (10%)
Japuni: JPN reduces emissions unilaterally by 20% (10%)
Usuni: USA reduces emissions unilaterally by 20% (10%)
EUJap: EU15 and JPN reduce emissions bilaterally by 20% (10%)
EUUS: EU15 and USA reduce emissions bilaterally by 20% (10%)
JapUS: JPN and USA reduce emissions bilaterally by 20% (10%)

Table II summarises the results.

Table II also decomposes the overall welfare effects. The domestic effect measures the costs of emission abatement *if the region were autarkic*. The international effects cover the rest, including terms-of-trade and size effects. The international effects are predominantly positive for the USA, predominantly negative for the EU15, while JPN shows a mixed picture.

4. Simple Model

The CGE has 11 regions, but only 3 reduce their emissions: the EU15, JPN and the USA. So, we consider a game with 3 players. The other 8 regions are dummy players, playing a default strategy of zero emission reduction.

Table II. Emission reduction in 2010 (relative to 1990), income loss in 2010 (relative to business as usual), and the decomposition of income loss in domestic and international effects

Emission reduction (%)			Loss of income (%)			Domestic			International		
USA	EU15	JPN	USA	EU15	JPN	USA	EU15	JPN	USA	EU15	JPN
10	10	10	0.00	0.72	0.15	0.21	0.19	0.06	–0.21	0.52	0.10
0	10	0	–0.72	0.21	0.00	0.00	0.19	0.00	–0.72	0.02	0.00
0	0	10	–0.57	0.02	0.23	0.00	0.00	0.06	–0.78	0.02	0.17
10	0	0	0.35	0.14	0.00	0.21	0.00	0.00	0.14	0.14	0.00
0	10	10	–0.45	0.18	0.19	0.00	0.19	0.06	–0.45	–0.01	0.13
10	10	0	0.54	0.22	0.00	0.21	0.19	0.00	–0.33	0.03	0.00
10	0	10	0.19	0.02	0.19	0.21	0.00	0.06	–0.02	0.02	0.13
20	20	20	1.01	0.75	0.54	0.58	0.47	0.23	0.43	0.28	0.31
0	20	0	–0.58	0.73	0.00	0.00	0.47	0.00	–0.58	0.26	0.00
0	0	20	–0.47	0.04	0.61	0.00	0.00	0.23	–0.47	0.04	0.38
20	0	0	0.93	0.54	–0.04	0.58	0.00	0.00	0.35	0.54	–0.04
0	20	20	–0.51	0.70	0.58	0.00	0.47	0.23	–0.51	0.22	0.35
20	20	0	0.97	0.73	–0.08	0.58	0.47	0.00	0.39	0.26	–0.08
20	0	20	0.95	0.07	0.50	0.58	0.00	0.23	0.37	0.07	0.27

4.1. NO LEAKAGE: MODEL

We fit two specifications to the outcomes of the CGE, both with two variants. Both specifications simplify (1). Note that running a CGE as complicated as WAGEM is time consuming. We therefore only have a limited number of "observations". Note also that WAGEM is but one of many CGEs for this type of analysis. We therefore opted for sensitivity analyses rather than improving the response surface of WAGEM.

Because of the strong correlation between emission reduction and emission reduction costs, we cannot reliably estimate a function similar to (1), that is, not with the number of observations available – see Table III. For the same reason, the goodness of fit is about the same for both simplifications. We cannot say which is a better approximation to the CGE results.

The first formulation (T1) is as follows. The costs of emission reduction are given by (10), for player 1, with $f(x) = \alpha x^2$, $g(y) = \chi y$ and $h(z) = 0$.

$$\frac{C_1}{Y_1} = \alpha_1 R_1^2 + \chi_1(R_1 - 0.5R_2 - 0.5R_3) \tag{10}$$

and similar for players 2 and 3. A more general version (T1′) of (10) is

$$\frac{C_1}{Y_1} = \alpha_1 R_1^2 + \chi_{11} R_1 + \chi_{12} R_2 + \chi_{13} R_3. \tag{10'}$$

Table III. Parameter estimates[a]

		α_i	β_i	χ_i	χ_{i1}	χ_{i2}	χ_{i3}	R^2
JPN	NT	0.142						0.983
		(0.006)						
(14)	T2	0.148	0.076					0.991
		(0.005)	(0.023)					
(10)	T1	0.133		0.003				0.990
		(0.005)		(0.001)				
	T1&2	0.143	0.052	0.001				0.991
		(0.012)	(0.054)	(0.003)				
(10′)[b]	T1′	0.057			0.017	–0.000	–0.003	1.000
		(0.000)			(0.001)	(0.001)	(0.001)	0.986
(16′)	T2′	0.151				–0.015	–0.002	0.991
		(0.006)				(0.006)	(0.006)	
USA	NT	0.244						0.809
		(0.048)						
(14)	T2	0.351	0.949					0.907
		(0.048)	(0.282)					
(10)	T1	0.159		0.032				0.913
		(0.042)		(0.009)				
	T1&2	0.239	0.020	0.430				0.919
		(0.102)	(0.016)	(0.498)				
(10′)[b]	T1′	0.149			–0.018	0.033	–0.016	0.968
		(0.016)			(0.009)	(0.009)	(0.009)	0.737
(16′)	T2′	0.312			–0.074		–0.080	0.890
		(0.049)			(0.049)		(0.049)	
EU15	NT	0.191						0.721
		(0.026)						
(14)	T2	0.182	–0.169					0.758
		(0.026)	(0.136)					
(10)	T1	0.215		–0.009				0.768
		(0.030)		(0.006)				
	T1&2	0.207	–0.007	–0.056				0.769
		(0.045)	(0.010)	(0.216)				
(10′)[b]	T1′	0.123			–0.000	0.012	0.008	0.931
		(0.018)			(0.005)	(0.005)	(0.005)	0.521
(16′)	T2′	0.164			–0.007	0.061		0.813
		(0.029)			(0.029)	(0.029)		

[a]Standard deviations are given in parentheses.
[b]The parameters of Equation (10′) are estimated separately. The domestic effect is used to estimate α; the R^2 is in the top row; the international effects of Table II are used to estimate the χs; the R^2 is in the bottom row.

The properties of (10) and (10′) are very similar. However, we cannot reliably estimate the parameters of (10′). Therefore, we estimate the parameters of Equation (10′) separately. The αs are estimated from the domestic effects in Table II; the χs are estimated from the international effects in Table II. See Table III for the results.

The benefits of emission reduction are given by

$$\frac{B_1}{Y_1} = \gamma_1(R_1E_1 + R_2E_2 + R_3E_3). \tag{11}$$

That is, benefits of emission reduction depend linearly on the avoided emissions in all three regions.

The first order condition for non-cooperative behaviour is, for player 1

$$2\alpha_1Y_1R_1 + \chi_1Y_1 - \gamma_1E_1Y_1 = 0 \Leftrightarrow R_1 = \frac{\gamma_1E_1 - \chi_1}{2\alpha_1}. \tag{12}$$

In this formulation, the marginal costs of emission reduction, and hence the optimal emission abatement, are not affected by emission reduction in other regions. The optimum, however, does shift if $\chi_1 \neq 0$. If we use (10′) instead of (10), (12) would not be affected if $\chi_1 = \chi_{11}$. We argue above that $\chi_1 > O$, so that non-cooperative optimal emission reduction falls. The reason is straightforward. Increasing emission control relative to other regions would increase costs by worsening terms-of-trade. Of course, if $\chi_1 < 0$, the argument is reversed. We estimate χ_1 below.

The first order condition for cooperative behaviour is, for player 1

$$\begin{aligned} &2\alpha_1Y_1R_1 + \chi_1Y_1 - 0.5\chi_2Y_2 - 0.5\chi_3Y_3 - (\gamma_1Y_1 + \gamma_2Y_2 + \gamma_3Y_3)E_1 = 0 \Leftrightarrow \\ &R_1 = \frac{(\gamma_1Y_1 + \gamma_2Y_2 + \gamma_3Y_3)E_1 - \chi_1Y_1 + 0.5\chi_2Y_2 + 0.5\chi_3Y_3}{2\alpha_1Y_1}. \end{aligned} \tag{13}$$

The marginal costs of emission reduction are independent of the spillover effects, but the regions do take the welfare effect in other regions into account. If we use (10′) instead of (10), (12) would not be affected if $\chi_1 = \chi_{11}$, $0.5\chi_2 = -\chi_{21}$, and $0.5\chi_3 = -\chi_{31}$. The impact of spillover effects on cooperative emission control is ambiguous as it depends on whether $0.5\chi_2Y_2 + 0.5\chi_3Y_3 - \chi_1Y_1$ is positive or negative.

As the effect of spillover effects on cooperative emission control is ambiguous, so is the effect on incentives to cooperate. Therefore, we turn to empirical estimates of the parameters of (10).

In the second formulation (T2), the costs of emission reduction are given by (14), with $f(x) = \alpha x^2$, $g(x) = 0$ and $h(z) = \beta z$:

$$\frac{C_1}{Y_1} = \alpha_1R_1^2 + \beta_1\left(\frac{C_2 + C_3}{Y_2 + Y_3}\right). \tag{14}$$

That is, costs of emission reduction depend on domestic emission reduction and the costs of emission reduction in the other regions.

Equation (14) has to be rewritten:

$$\begin{pmatrix} 1 & -\dfrac{\beta_1 Y_1}{Y_2 + Y_3} & -\dfrac{\beta_1 Y_1}{Y_2 + Y_3} \\ -\dfrac{\beta_2 Y_2}{Y_1 + Y_3} & 1 & -\dfrac{\beta_2 Y_2}{Y_1 + Y_3} \\ -\dfrac{\beta_3 Y_3}{Y_1 + Y_2} & -\dfrac{\beta_3 Y_3}{Y_1 + Y_2} & 1 \end{pmatrix} \begin{pmatrix} C_1 \\ C_2 \\ C_3 \end{pmatrix} = \begin{pmatrix} \alpha_1 R_1^2 Y_1 \\ \alpha_2 R_2^2 Y_2 \\ \alpha_3 R_3^2 Y_3 \end{pmatrix} \tag{15}$$

or, in matrix form,

$$C = A^{-1} D \tag{16}$$

where C is the vector of total emission reduction costs, D the vector of domestic emission reduction costs, and A is the parameter matrix as in (15). Estimating (16) is not easy because of parameter restrictions, and because our data set is too limited to apply methods like 2SLS and 3SLS (e.g., Greene 1991). We proceed by two alternative routes. First, we estimate Equation (14) directly, ignoring problems of endogeneity. Second, we estimate an unrestricted version (T2′) of (16), that is:

$$\frac{C_1}{Y_1} = \alpha_{11} R_1^2 + \chi_{12} R_2^2 + \chi_{13} R_3^2. \tag{16′}$$

Equation (16′) has 9 parameters, while Equation (16) has only 6. Note that the two alternative ways of estimation lead to approximately the same conclusions (see below).

Summarising, the following forms of Equation (1) are used:

$$f_i(R_i) = \alpha_i R_i^2 \qquad \text{all cases}$$

$$g_i(R_i, R_j, R_k) = \begin{cases} 0 & \text{NT, T2, T2}' \\ \chi_i (R_i - \frac{1}{2} R_j - \frac{1}{2} R_k) & \text{T1, T1 + 2} \\ \chi_{ii} R_i + \chi_{ij} R_j + \chi_{ik} R_k & \text{T1}' \end{cases}$$

$$h_i(C_j, C_k) = \begin{cases} 0 & \text{NT, T1, T1}' \\ \beta_i \left(\dfrac{C_j + C_k}{Y_j + Y_k} \right) & \text{T2, T1 + 2} \\ \chi_{ij} R_j^2 + \chi_{ik} R_k^2 & \text{T2}' \end{cases}$$

Subtracting the benefits – Equation (8) – the objective function becomes:

$$W = C - B = A^{-1}D - B. \tag{17}$$

Without cooperation, optimal emission control follows from solving:

$$\begin{aligned}&\max_{R_1}\ (1\quad 0\quad 0)\ (A^{-1}D - B)\\ &\max_{R_2}\ (0\quad 1\quad 0)\ (A^{-1}D - B)\\ &\max_{R_3}\ (0\quad 0\quad 1)\ (A^{-1}D - B)\end{aligned} \tag{18}$$

With cooperation, optimal emission control follows from solving

$$\max_{R_1,R_2,R_3}\ (1\quad 1\quad 1)\ (A^{-1}D - B). \tag{19}$$

The first order conditions of (18) are, for player 1

$$(1\ 0\ 0)\begin{pmatrix} 1 & -\dfrac{\beta_1 Y_1}{Y_2+Y_3} & -\dfrac{\beta_1 Y_1}{Y_2+Y_3}\\ -\dfrac{\beta_2 Y_2}{Y_1+Y_3} & 1 & -\dfrac{\beta_2 Y_2}{Y_1+Y_3}\\ -\dfrac{\beta_3 Y_3}{Y_1+Y_2} & -\dfrac{\beta_3 Y_3}{Y_1+Y_2} & 1 \end{pmatrix}^{-1}\begin{pmatrix}2\alpha_1 R_1 Y_1\\ 0\\ 0\end{pmatrix} -$$

$$(1\ 0\ 0)\begin{pmatrix}\gamma_1 E_1 Y_1\\ \gamma_2 E_2 Y_2\\ \gamma_3 E_3 Y_3\end{pmatrix} = 0\ (20) \tag{20}$$

which "simplifies" to

$$\frac{1+\dfrac{\beta_2 Y_2}{Y_1+Y_3}\dfrac{\beta_3 Y_3}{Y_1+Y_2}}{1-\dfrac{\beta_2 Y_2}{Y_1+Y_3}\dfrac{\beta_3 Y_3}{Y_1+Y_2}+\dfrac{\beta_1 Y_1}{Y_2+Y_3}\left[\dfrac{\beta_2 Y_2}{Y_1+Y_3}\left(2\dfrac{\beta_3 Y_3}{Y_1+Y_2}+1\right)+\dfrac{\beta_3 Y_3}{Y_1+Y_2}\right]}2\alpha_1 R_1 = \gamma_1 E_1 \tag{20$'$}$$

and similar for players 2 and 3. So, the spillover effects do affect non-cooperative optimal emission reduction, because the solution of (18) would be very different if the βs were zero. However, the optimal emission reduction in one region is independent of other regions' actions. Spillover effects also affect welfare in the optimum. These effects are ambiguous, depending on the interplay of the parameters in the inverted matrix, as is clear from (20$'$).

The first order conditions of (19) are, for emission reductions by player 1

$$(1\ \ 1\ \ 1)\begin{pmatrix} 1 & -\dfrac{\beta_1 Y_1}{Y_2+Y_3} & -\dfrac{\beta_1 Y_1}{Y_2+Y_3} \\ -\dfrac{\beta_2 Y_2}{Y_1+Y_3} & 1 & -\dfrac{\beta_2 Y_2}{Y_1+Y_3} \\ -\dfrac{\beta_3 Y_3}{Y_1+Y_2} & -\dfrac{\beta_3 Y_3}{Y_1+Y_2} & 1 \end{pmatrix}^{-1}\begin{pmatrix} 2\alpha_1 R_1 Y_1 \\ 0 \\ 0 \end{pmatrix} -$$

$$(1\ \ 1\ \ 1)\begin{pmatrix} \gamma_1 E_1 Y_1 \\ \gamma_2 E_2 Y_2 \\ \gamma_3 E_3 Y_3 \end{pmatrix} = 0 \tag{21}$$

which "simplifies" to

$$\frac{1+\dfrac{\beta_2 Y_2}{Y_1+Y_3}+\dfrac{\beta_3 Y_3}{Y_1+Y_2}+\dfrac{\beta_2 Y_2}{Y_1+Y_3}\dfrac{\beta_3 Y_3}{Y_1+Y_2}}{1-\dfrac{\beta_2 Y_2}{Y_1+Y_3}\dfrac{\beta_3 Y_3}{Y_1+Y_2}+\dfrac{\beta_1 Y_1}{Y_2+Y_3}\left[\dfrac{\beta_2 Y_2}{Y_1+Y_3}\left(2\dfrac{\beta_3 Y_3}{Y_1+Y_2}+1\right)+\dfrac{\beta_3 Y_3}{Y_1+Y_2}\right]}2\alpha_1 R_1 Y_1 =$$

$$\gamma_1 E_1 Y_1 + \gamma_2 E_2 Y_2 + \gamma_3 E_3 Y_3 \tag{21$'$}$$

and similar for the emission reduction by players 2 and 3. The solution to (21) would be different if the βs were zero, so the spillover effects affect cooperative optimal emission reduction and hence the difference between non-cooperative and cooperative action. Again, the effect is ambiguous, so that we turn to empirical estimates of the parameters.

The two alternative formulations thus include different aspects of the spillover effects. In the first formulation, trade effects are driven by the *relative* emission abatement of one country compared to the others. In the second formulation, trade effects are driven by the costs of emission abatement and thus, after some manipulation, by the *absolute* emission abatement in other countries. Table III shows the estimated parameters for the cases discussed above.

Of course, we can combine the two models, but then we lose sight on the different aspects. Besides, the parameter estimates are insignificant in that case. See Table III.

4.2. NO LEAKAGE: RESULTS

Table IV shows results of the two models presented above. Table V summarises the findings. The parameters are estimated, using ordinary least squares because of data limitations, from the outcomes of the CGE of the previous section. In addition, we present the results of a model without any international trade interaction, calibrated to the same CGE. See Table III.

Table IV. Optimal emission reduction and pay-off without leakage[a]

	USA	EU15	JPN	USA	EU15	JPN
No cooperation						
NT	7.0	4.9	4.7	25.8	31.3	35.1
	(5.8–8.7)	(4.3–5.7)	(4.5–4.9)	(22.5–30.4)	(26.8–37.7)	(30.0–42.3)
T1	0.6	6.5	3.7	32.9	13.3	18.4
	(0.0–4.6)	(4.4–9.3)	(3.1–4.3)	(27.4–41.5)	(2.3–28.9)	(5.5–38.1)
T1′	11.4	7.6	11.6	39.3	31.8	48.3
	(10.3–12.7)	(6.7–8.9)	(11.6–11.6)	(12.9–70.5)	(13.5–53.3)	(41.2–57.2)
T2	5.1	5.5	4.5	20.2	27.4	30.2
	(4.6–5.6)	(4.9–6.1)	(4.4–4.6)	(19.4–20.6)	(25.8–28.6)	(27.2–32.9)
T2′	5.3	5.7	4.4	28.6	24.8	18.4
	(4.6–6.3)	(4.9–6.9)	(4.3–4.6)	(22.7–32.5)	(20.6–30.7)	(16.0–21.8)
Full cooperation						
NT	20.9	14.7	14.0	11.2	60.3	94.4
	(17.5–26.0)	(13.0–17.1)	(13.5–14.6)	(8.9–12.2)	(51.0–74.3)	(79.7–115.6)
T1	20.4	18.3	19.8	55.5	32.4	91.3
	(15.1–29.6)	(15.5–22.0)	(15.6–23.6)	(36.9–75.8)	(28.8–46.3)	(54.1–139.3)
T1′	21.6	14.3	50.0	114.4	70.4	9.9
	(11.4–34.3)	(8.8–21.7)	(50.0–50.0)	(75.0–149.5)	(22.5–133.3)	(–39.9–73.5)
T2	11.4	9.8	29.6	0.5	81.5	3.9
	(11.0–11.8)	(9.8–9.8)	(23.4–37.3)	(0.6–2.7)	(60.3–115.3)	(–35.8–27.2)
T2′	29.7	13.6	16.3	–95.4	38.5	40.8
	(16.1–50.0)	(10.3–19.8)	(13.4–20.6)	(–317.4–2.1)	(27.0–78.5)	(29.1–72.8)
Coalition of USA and EU15						
NT	13.9	9.8	4.7	26.0	47.8	68.3
	(11.6–17.3)	(8.7–11.4)	(4.6–4.9)	(23.1–29.6)	(40.4–58.7)	(58.3–82.7)
T1	9.4	13.7	3.7	48.7	22.7	64.4
	(6.4–14.8)	(11.4–16.8)	(3.1–4.3)	(44.8–55.3)	(11.7–39.0)	(49.0–88.6)
T1′	15.1	11.6	11.6	40.2	32.6	69.9
	(7.3–24.9)	(7.2–17.4)	(11.6–11.6)	(24.8–63.8)	(9.1–69.4)	(32.5–118.1)
T2	10.2	8.8	4.5	14.8	44.6	52.9
	(9.9–10.5)	(8.7–8.8)	(4.4–4.6)	(11.9–16.5)	(41.4–48.7)	(51.7–53.9)
T2′	15.6	8.9	4.4	7.3	39.7	27.6
	(10.3–32.8)	(7.1–11.8)	(4.3–4.6)	(–118.6–17.5)	(20.2–71.4)	(21.7–45.6)

Table IV. Continued

	USA	EU15	JPN	USA	EU15	JPN
Coalition of USA and JPN						
NT	13.9 (11.6–17.3)	4.9 (4.3–5.7)	9.4 (9.0–9.7)	18.4 (16.8–20.5)	57.0 (48.8–69.0)	55.3 (46.8–67.9)
T1	9.4 (6.3–14.8)	6.5 (4.4–9.3)	18.5 (16.8–19.9)	54.8 (53.4–60.3)	39.5 (36.6–49.3)	30.5 (9.5–59.5)
T1′	6.6 (1.5–13.0)	7.6 (6.7–8.9)	47.8 (46.1–49.5)	139.4 (90.6–194.9)	54.8 (13.3–108.3)	–47.6 (–63.6–26.3)
T2	6.3 (5.7–6.8)	5.5 (4.9–6.1)	16.3 (14.4–17.9)	20.5 (18.2–23.0)	44.7 (40.7–48.6)	21.6 (14.3–28.3)
T2′	12.4 (9.6–17.5)	5.7 (4.9–6.9)	10.5 (9.5–11.9)	24.7 (19.8–25.3)	43.6 (30.8–67.1)	20.9 (18.0–26.1)
Coalition of EU15 and JPN						
NT	7.0 (5.8–8.7)	9.8 (8.7–11.4)	9.4 (9.0–9.7)	40.6 (35.8–47.1)	29.3 (25.4–35.0)	44.4 (38.1–53.4)
T1	0.6 (0.0–4.6)	11.0 (8.4–14.5)	5.1 (6.9–3.1)	53.3 (54.4–56.8)	8.1 (–0.2–23.0)	29.1 (14.1–50.2)
T1′	11.4 (10.3–12.7)	7.3 (3.9–11.8)	31.3 (29.3–33.3)	86.2 (33.0–155.5)	49.2 (21.6–82.3)	14.8 (6.0–27.3)
T2	6.3 (5.5–7.2)	7.2 (6.3–8.4)	21.7 (21.1–22.4)	19.0 (9.6–24.8)	51.7 (48.5–53.3)	11.6 (8.3–15.8)
T2′	29.7 (16.1–50.0)	11.7 (9.2–15.9)	9.0 (8.1–10.2)	57.8 (38.4–96.9)	21.8 (17.8–25.5)	33.7 (27.4–44.8)

[a]The range of emission reduction efforts and pay-offs are given in brackets. These ranges are found by varying the parameters by one standard deviation.

We assume that the marginal costs of carbon dioxide emissions are \$200/tC for all three regions. This is high (cf. Tol 1999), but we need this to generate substantial emission reductions.

Without trade interactions, except for the coalition between the USA and the EU15, the grand coalition nor any of the three other possible coalitions of two players is internally stable. That is, in each coalition, there is one player that is better off in the non-cooperative case and thus has an incentive to leave the coalition. This conclusion holds for the best guess as well as for the sensitivity analyses.

Table V. Stable coalitions without leakage[a]

		NT	T1	T1′	T2	T2′
Internal	high	Ø	{USA, EU15} {USA, JPN}	Ø	Ø	Ø
	mid	{USA, EU15}	{USA, EU15} {USA, JPN}	{USA, EU15}	Ø	Ø
	low	{USA, EU15}	{USA, EU15} {USA, JPN}	Ø	Ø	Ø
External[b]	high	{EU15, JPN}	{USA, JPN}	{USA, EU15} {EU15, JPN}	{USA, EU15} {EU15, JPN}	Ø
	mid	{EU15, JPN}	{USA, JPN}	{USA, EU15}	{USA, EU15} {EU15, JPN}	{USA, JPN}
	low	{EU15, JPN}	{USA, JPN}	{USA, EU15}	{USA, EU15} {EU15, JPN}	{USA, JPN}
Stable	high	Ø	{USA, JPN}	Ø	Ø	Ø
	mid	Ø	{USA, JPN}	{USA, EU15}	Ø	Ø
	low	Ø	{USA, JPN}	Ø	Ø	Ø

[a]Stability based on the theory of cartel stability (Carraro et al. 1997):
Notation:
$P_i(s)$ is the value of player i – who is not a member of s – for joining coalition s.
$Q_i(s)$ is the value of player i – who is not a member of s – for not joining coalition s.
Definition:
A coalition is internally stable iff: $P_i(s) > Q_i(s \setminus i)$ for all $i \notin s$.
A coalition is externally stable iff: $P_i(s \cup i) < Q_i(s)$ for all $i \in s$.
A coalition is stable iff it is both internally and externally stable.
[b]The grand coalition is externally stable by default.

In our first representation of trade interactions, the grand coalition is in the γ-core, that is, all players are better off with full cooperation that with non-cooperation. The grand coalition, however, is internally instable, using the myopic stability criterion of Carraro: The EU15 is better of if it plays as a singleton, and the USA and JPN form a coalition. The USA and JPN are better off in a coalition than as singletons, so the grand coalition is also internally instable using the far-sighted stability criterion of Chwe (1994). The EU15 does not want to from a coalition with JPN alone, but it does with the USA. The USA and JPN would like to form a coalition with the EU15, either of size 2 or 3. The grand coalition is not stable in all sensitivity analyses. The coalition between the USA and the EUI5, and the coalition between the USA and EU15 are internally stable in all sensitivity analyses. The EU15 never wants to cooperate with JPN alone.

A similar picture emerges for the alternative specification of (10′), and the sensitivity analysis around its parameters. Full cooperation is unstable, but smaller coalitions are viable, notably between the EU15 and the USA.

In our second representation of trade interactions, the grand coalition nor any of the three possible coalitions of two players is internally stable. This holds for the best guess as well as for the sensitivity analysis. It holds also for the alternative estimates of (16′), as well as the sensitivity analysis around its parameters. Although we have difficulty estimating the parameters of (14) and (16′), the results are robust against uncertainties in the estimates.

In sum, without trade effects, cooperation is hard to achieve. This is because emission reduction is a public good. If we extend the model to include trade effects driven by emission abatement in one country relative to emission abatement in other countries, cooperation is easier. If instead trade effects are driven by total emission abatement in other countries, cooperation is as difficult as without trade. The intuition behind the last result is as follows. The fact that other players' actions have an additional impact on one's pay-off, is an additional reason to want them to cooperate. However, cooperation would also place additional demands on oneself. In our case, the two effects approximately cancel, and this is true for a wide range of parameter estimates. The intuition behind the second result is as follows. The above reasoning still holds. However, if trade effects depend on relative actions, then there is an additional reason for coordination.

4.3. LEAKAGE: MODEL

Above, we investigate the effects of international trade and investment on the costs of emission reduction. International trade and investment also affect emissions, so-called carbon leakage. We now add leakage to the model. Because the cost function specification (10) and (10′) as well as (16) and (16′) behave much the same, we restrict the attention to (10) and (16).

With leakage, Equation (11) has to be replaced with:

$$\begin{aligned}\frac{B_1}{Y_1} = {} & \gamma_1\{R_1[(1+k_1)E_1 - 0.5k_2E_2 - 0.5k_3E_3] + \\ & R_2[(1+k_2)E_2 - 0.5k_1E_1 - 0.5k_3E_3] + \\ & R_3[(1+k_3)E_3 - 0.5k_1E_1 - 0.5k_2E_2]\}\end{aligned} \tag{22}$$

The first order condition for non-cooperative behaviour is, for player 1

$$\begin{aligned}& 2\alpha_1Y_1R_1 + \chi_1Y_1 - \gamma_1Y_1[(1+k_1)E_1 - 0.5k_2E_2 - 0.5k_3E_3] = 0 \Leftrightarrow \\ & R_1 = \frac{\gamma_1[(1+k_1)E_1 - 0.5k_2E_2 - 0.5k_3E_3] - \chi_1}{2\alpha_1}.\end{aligned} \tag{23}$$

Compared to the case without leakage ($k_i = 0$), optimal emission reduction goes up or down depending on the relative sizes of k and E. If economy 1 is relatively sensitive to the other regions' emission reduction (k is large) or if the emissions E of economy 1 are relatively large, optimal emission reduction of region 1 would increase compared to the case without leakage.

The first order condition for cooperative behaviour is, for player 1

$$2\alpha_1 Y_1 R_1 + \chi_1 Y_1 - 0.5\chi_2 Y_2 - 0.5\chi_3 Y_3 - (\gamma_1 Y_1 + \gamma_2 Y_2 + \gamma_3 Y_3)[(1+k_1)E_1 - 0.5k_2 E_2 - 0.5k_3 E_3] = 0 \Leftrightarrow R_1 = \frac{(\gamma_1 Y_1 + \gamma_2 Y_2 + \gamma_3 Y_3)[(1+k_1)E_1 - 0.5k_2 E_2 - 0.5k_3 E_3] - \chi_1 Y_1 + 0.5\chi_2 Y_2 + 0.5\chi_3 Y_3}{2\alpha_1 Y_1}. \tag{24}$$

In the second formulation, the first order conditions for non-cooperative behaviour are, for player 1

$$(1\ \ 0\ \ 0)\begin{pmatrix} 1 & -\dfrac{\beta_1 Y_1}{Y_2+Y_3} & -\dfrac{\beta_1 Y_1}{Y_2+Y_3} \\ -\dfrac{\beta_2 Y_2}{Y_1+Y_3} & 1 & -\dfrac{\beta_2 Y_2}{Y_1+Y_3} \\ -\dfrac{\beta_3 Y_3}{Y_1+Y_2} & -\dfrac{\beta_3 Y_3}{Y_1+Y_2} & 1 \end{pmatrix}^{-1} \begin{pmatrix} 2\alpha_1 R_1 Y_1 \\ 0 \\ 0 \end{pmatrix} -$$

$$(1\ \ 0\ \ 0)\begin{pmatrix} \gamma_1 Y_1[(1+k_1)E_1 - 0.5k_2 E_2 - 0.5k_3 E_3] \\ \gamma_2 Y_2[(1+k_2)E_2 - 0.5k_1 E_1 - 0.5k_3 E_3] \\ \gamma_3 Y_3[(1+k_3)E_3 - 0.5k_1 E_1 - 0.5k_2 E_2] \end{pmatrix} = 0. \tag{25}$$

The first order conditions for cooperative behaviour are, for emission reductions by player 1

$$(1\ \ 1\ \ 1)\begin{pmatrix} 1 & -\dfrac{\beta_1 Y_1}{Y_2+Y_3} & -\dfrac{\beta_1 Y_1}{Y_2+Y_3} \\ -\dfrac{\beta_2 Y_2}{Y_1+Y_3} & 1 & -\dfrac{\beta_2 Y_2}{Y_1+Y_3} \\ -\dfrac{\beta_3 Y_3}{Y_1+Y_2} & -\dfrac{\beta_3 Y_3}{Y_1+Y_2} & 1 \end{pmatrix}^{-1} \begin{pmatrix} 2\alpha_1 R_1 Y_1 \\ 0 \\ 0 \end{pmatrix} -$$

$$(1\ \ 1\ \ 1)\begin{pmatrix} \gamma_1 Y_1[(1+k_1)E_1 - 0.5k_2 E_2 - 0.5k_3 E_3] \\ \gamma_2 Y_2[(1+k_2)E_2 - 0.5k_1 E_1 - 0.5k_3 E_3] \\ \gamma_3 Y_3[(1+k_3)E_3 - 0.5k_1 E_1 - 0.5k_2 E_2] \end{pmatrix} = 0. \tag{26}$$

4.4. LEAKAGE: RESULTS

Table VI shows results of the two models presented above. The parameters are the same as above (central estimates only). We assume a leakage of 10%, with 5% and 15% as sensitivity analysis. Table VII provides a summary.

Without trade interactions, the grand coalition nor any of the three possible coalitions of two players is internally stable. That is, in each coalition, there is one player that is better of in the non-cooperative case and thus has an incentive to leave the coalition. This conclusion holds for the best guess as well as for the sensitivity analyses. The only qualitative difference with the case without leakage is that the coalition between the USA and EU15 is no longer internally stable.

In our first representation of trade interactions, the grand coalition is in the γ-core, that is, all players are better off with full cooperation that with non-cooperation. The grand coalition, however, is internally instable, using the myopic stability criterion of Carraro (1997): The EU15 is better of if it plays as a singleton, and the USA and JPN form a coalition. The USA and JPN are better off in a coalition than as singletons, so the grand coalition is also internally instable using the far-sighted stability criterion of Chwe (1994).

In our second representation of trade interaction, the grand coalition nor any of the three possible coalitions of two players is internally stable. This holds for the best guess as well as for the sensitivity analysis.

In our formulation, leakage alters the strategic interests of the players, even though, in the chosen representation, leakage does not alter relative and marginal abatement costs. However, leakage does alter the effectiveness of emission reduction.

5. Conclusion

A number of conclusions emerge from the analyses in this paper. These conclusions are reached on the basis of admittedly simple representations of complex interactions.

It matters what drives international spillover effects. If spillover effects are mostly determined by the total costs of other countries' emission reduction efforts (or by the absolute emission reduction abroad – the size effects), the incentives to cooperate are about as weak as if there were no spillovers whatsoever. Much as a country would like other countries to take spillover effects into account, it does not want to do so itself. In our specification, for a wide range of parameters, the two effects largely cancel – actually, cooperation becomes a little harder, a hardly noticeable effect as cooperation was already virtually absent in the no-trade case.

However, if spillover effects are mostly driven by relative emission reductions (the terms-of-trade effects), incentives to cooperate are stronger than without considering spillovers. The intuition behind this result is that the interdependence between countries' emission reduction policies is stronger so that international coordination has a higher pay-off.

Table VI. Optimal emission reduction and pay-off with leakage[a]

	Reduction (percent)			Pay-off (million dollar)		
	USA	EU15	JPN	USA	EU15	JPN
No cooperation						
NT	7.3	5.0	3.5	25.0	31.5	36.2
	(7.1–7.5)	(4.9–5.0)	(2.9–4.1)	(24.6–25.4)	(31.4–31.6)	(35.7–36.8)
T1	1.1	6.6	2.4	30.2	14.5	20.3
	(0.9–1.4)	(6.5–6.6)	(1.8–3.1)	(28.9–31.6)	(13.9–15.1)	(19.4–21.1)
T2	5.4	5.6	3.3	19.7	27.4	31.1
	(5.3–5.5)	(5.6–5.6)	(2.8–3.9)	(19.4–20.0)	(27.3–27.4)	(30.2–31.4)
Full cooperation						
NT	22.0	14.9	10.5	1.8	60.1	102.7
	(21.4–22.5)	(14.8–15.0)	(8.7–12.3)	(–3.1–6.6)	(60.0–60.2)	(98.8–106.1)
T1	22.1	18.5	16.0	37.4	34.9	105.5
	(21.3–22.9)	(18.4–18.5)	(14.1–17.9)	(28.0–46.6)	(33.7–36.1)	(98.7–111.7)
T2	11.4	9.8	29.7	0.5	81.5	3.9
	(11.4–11.4)	(9.8–9.8)	(29.7–29.7)	(0.5–0.5)	(81.5–81.5)	(3.9–3.9)
Coalition of USA and EU15						
NT	14.6	10.0	3.5	22.9	48.9	70.8
	(14.3–15.0)	(9.9–10.0)	(2.9–4.1)	(21.3–24.5)	(48.3–49.4)	(69.6–72.0)
T1	10.5	13.8	2.4	43.2	24.9	68.2
	(10.0–11.1)	(13.8–13.9)	(1.8–3.1)	(40.3–46.0)	(23.8–26.0)	(66.3–70.0)
T2	10.2	8.8	3.3	14.2	43.6	52.8
	(10.2–10.2)	(8.8–8.8)	(2.8–3.9)	(13.9–14.5)	(43.1–44.1)	(52.6–52.9)
Coalition of USA and JPN						
NT	14.6	5.0	7.0	14.3	57.5	59.2
	(14.3–15.0)	(4.9–5.0)	(5.8–8.2)	(12.2–16.4)	(57.2–57.7)	(57.4–60.7)
T1	10.5	6.6	15.9	46.2	41.9	39.6
	(10.0–11.1)	(6.5–6.6)	(14.6–17.1)	(41.8–50.5)	(40.7–43.1)	(35.2–43.7)
T2	6.3	5.6	16.3	20.5	44.7	21.8
	(6.3–6.3)	(5.6–5.6)	(16.3–16.3)	(20.5–20.6)	(44.7–44.7)	(21.7–21.9)
Coalition of EU15 and JPN						
NT	7.3	10.0	7.0	39.1	28.3	47.2
	(7.1–7.5)	(9.9–10.0)	(5.8–8.2)	(38.3–39.8)	(27.8–28.8)	(46.0–48.3)
T1	1.1	11.2	2.6	47.9	8.9	31.2
	(0.9–1.4)	(11.1–11.2)	(1.3–3.8)	(45.2–50.6)	(8.6–9.2)	(30.3–31.9)
T2	6.3	7.2	21.7	19.0	51.7	11.6
	(6.3–6.3)	(7.2–7.2)	(21.7–21.7)	(19.0–19.0)	(51.7–51.7)	(11.6–11.6)

[a]The range of emission reduction efforts and pay-offs are given in brackets. These ranges are found by varying the parameters by one standard deviation.

Table VII. Stable coalitions with leakage[a]

	NT	T1	T2
Internally stable coalitions	Ø	{USA, EU15}, {USA, JPN}	Ø
Externally stable coalitions[a]	{EU15, JPN}	{USA, JPN}	{USA, EU15}, {EU15, JPN}
Stable coalitions	Ø	{USA, JPN}	Ø

[a]See the footnotes to Table V.

Leakage changes the numbers but not the qualitative insights. The intuition is straightforward. On the one hand, leakage means that a country has less control over its own emissions. On the other hand, with leakage, a country has some control over other countries' emissions. Essentially, leakage implies that a country has control over different base emissions. Leakage thus changes the relative importance of countries, but not their incentives to abate or cooperate.

Clearly, the analysis in this paper is only a small step, and our understanding is far away from where we would like it to be. The most obvious shortcoming is that we use a static analysis for a dynamic problem. The functional forms are not as generic as can be, and the number of players is limited. Furthermore, the analysis should be extended to more linkages (e.g., technology) and to other issues (e.g., conventional air pollution). Finally, for lack of observations of the effects of greenhouse gas emission reduction policies, we had to rely on "simulated data". All that is deferred to future research. For the moment, we conclude that international trade and carbon leakage are important considerations in the choice how much greenhouse gas emissions to reduce and whether and with whom to cooperate.

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Notes

1. Some may argue that $h = 0$. We separately analyse that case below.
2. Note that the costs of emission reduction are a function of leakage if emission reduction is expressed as absolute emission reduction, or as emission reduction relative to a fixed base year, or

as emission reduction relative to a base line that includes leakage. However, we express emission reduction relative to a base line excluding leakage.

3. The assumption is that the moved economic activity uses the exact same technology in the host country as it did in the origin country. *A priori*, there is little reason to assume that the technology would be more or less emission-intensive.

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